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CURRENT OPINION
Sports cardiology

European Association of Preventive Cardiology (EAPC) and European Association of Cardiovascular Imaging (EACVI) joint position statement: recommendations for the indication and interpretation of cardiovascular imaging in the evaluation of the athlete's heart

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1. Introduction

Athletic training is associated with a spectrum of morphologic and functional cardiac adaptations known as 'the athlete's heart'.[1,2] To the purpose of the present document an athlete is defined as an individual of young or adult age, either amateur or professional, who is engaged in regular exercise training and participate in official sports competition. Official sports competition is defined as an organized team or individual sports event that place a high premium on athletic excellence and achievement and is organized and scheduled in the agenda of Athletic Associations.[3]

A vast amount of literature has been assembled over the last two decades improving our understanding of the characteristics of physiologic cardiac remodelling in athletes. However, there are still areas of uncertainty regarding the differential diagnosis of the most marked expression of the athlete's heart, with certain inherited cardiac diseases, such as hypertrophic (HCM), dilated (DCM), or arrhythmogenic cardiomyopathy (AC) and left ventricular non-compaction (LVNC) cardiomyopathy.[4–7]

Indeed, in the more recent times, advances in technology, including three-dimensional (3D) echocardiography, speckle tracking echocardiography (STE), cardiac magnetic resonance (CMR), and multi-detector computed tomography (CT) have largely improved the diagnostic capabilities of the modern imaging modalities and made possible the correct identification of a broader spectrum of pathologic cardiovascular conditions that might occur in the athlete's population.

In 2015, an initial effort has been carried out by the European Association of Cardiovascular Imaging (EACVI) in order to guide appropriate interpretation of imaging in the context of athletes' evaluation.[8] After the initial interest raised by this document, further advances have been carried out in this field, including new international criteria for electrocardiogram (ECG) interpretation, updated recommendations for sport eligibility from the American College of Cardiology and American Heart Association, and further research in this field.[9–16]

Therefore, we believed it timely and appropriate to expand previous work and assemble a novel recommendation document with combined effort of experts from both the European Association of Preventive Cardiology (EAPC) and EACVI in order to properly address the determinants of cardiac remodelling, indications for imaging and clues for differential diagnosis with cardiac pathology. In addition, in this revised document we addressed number of pathologic conditions that are relevant to the cardiovascular evaluation of the athletes (and were not included in previous document), such as left-ventricular non-compaction, myocarditis, mitral valve prolapse, and bicuspid aortic valve (BAV).

2 Cardiovascular adaptations in athletes

2.1 Impact of gender, age, race, and body size

The quest for excellence in sports is associated with a plethora of electrical, structural and functional cardiac adaptations termed the 'athlete's heart'. Manifestations of the athlete's heart include a higher prevalence of electrocardiographic anomalies, balanced increase in the left and right cardiac cavity sizes, increased left ventricular (LV) wall thickness and superior indices of systolic and diastolic function, compared with sedentary individuals.[4,17–19] Such cardiac adaptations are usually modest and fall within accepted normal limits. Occasionally, however, athletes reveal marked electrical and structural expressions that overlap with those observed in cardiac diseases.

It is imperative that clinicians adopt an individualized approach to the interpretation of an athlete's evaluation, as expression of the athlete's heart is influenced by several factors (*Figure 1*). Body size has an important influence on cardiac dimensions, accounting for about 50% of the variability of LV cavity size and mass in highly trained athletes.[4,20] Therefore, when assessing the extent of cardiac remodelling, the absolute LV dimensions in an athlete should be viewed in the context of the body size.[4] Despite these observations, indexing the structural and functional parameters is still limited in the clinical practice. The limitations of current scaling methods is underscored by the fact that the most widely used method for calculation of the body surface area (BSA; the Dubois regression) is an empirically derived formula that was developed from nine cadaveric subjects and prone to significant errors. Contemporary studies have suggested the use of fat free mass, or (if impractical) the use of height for normalization of cardiovascular variables.[21]

Women who regularly engage in sports show similar cardiac adaptations compared with male counterparts but commonly to a lesser extent, in term of absolute values. Female athletes exhibit modest absolute increases in LV wall thickness and cavity size, as well as modest increases of right ventricular (RV) and bi-atrial cavity size when compared with sedentary women.[4,19,22,23]

Ethnicity has emerged as a major determinant of cardiac adaptation to exercise, with black athletes exhibiting a higher prevalence of electrocardiographic anomalies and significantly more LV hypertrophy in response to exercise training.[17,23–25] Electrocardiographic anomalies are present in up to 40% of black athletes with T-wave inversions being present in a fifth of the cohort.[26] Papadakis *et al.*[17] demonstrated that 13% of black athletes exhibit anterior T-wave inversion (V1–V4), which when associated with ST-segment elevation is likely to represent a feature of the 'black athlete's heart'. In addition, 12% black athletes exhibit a wall thickness >12 mm compared with only 2% of white athletes.[17] The challenge of differentiating between physiological LV

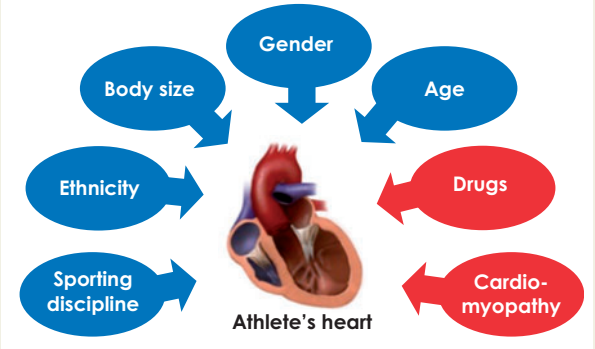

Figure 1 Figure depicts the main physiological (blue) and pathological (red) determinants that influence cardiac adaptations to exercise training in athletes.

hypertrophy and HCM in black athletes is further complicated by the fact that they exhibit similar LV cavity sizes to white athletes and a higher wall thickness to cavity ratio. Preliminary data from Arabic and Asian athletes suggest a similar or even lower prevalence of LV hypertrophy than in white athletes[27,28] (*Figure 2*).

With regard to age, some differences have been reported in senior compared with younger athletes; master athletes show lower LV volumes and mass compared with the younger counterpart by both echocardiography and CMR, even though both these parameters are still higher compared with age-matched untrained controls.[29–31] Systolic function, in terms ejection fraction and two-dimensional (2D) echocardiography strain imaging is usually preserved in master athletes and not different from younger ones; conversely, with aging, changes in diastolic function have been reported in master athletes with smaller *E* and *e′* waves and higher *A* and *a′* waves.[30] These changes in diastolic function reflect the normal aging process of the left ventricle and are similar to what occurs in untrained individual, therefore, it has accepted that exercise activity, while providing prolonged diastolic time associated with lower heart rate, however does not reduce the impairment of early diastolic filling induced by age.[32,33]

2.2 Impact of type of sport on cardiovascular adaptations

Cardiac adaptations in athletes mainly depend upon the characteristics, intensity, and cumulative duration of training protocols, with a 'dose-effect' relation. Usually, in professional athletes, training schedules involve >10–15 h/week of intensive exercise conditioning. In detail, isotonic (dynamic) exercise is associated with a substantial increase in cardiac output and reduction in peripheral vascular resistance; therefore, endurance training mainly results in volume overload; conversely, isometric (static) exercise is characterized by less increase in cardiac output and by a transient increase in peripheral resistances; therefore, it training is characterized by a pressure overload.[2,34–36] The first observation describing differences in cardiac adaptations in relation to the type of sport was reported in 1975 by Morganroth, who observed a concentric LV hypertrophy in isometric sports and an eccentric LV hypertrophy in isotonic disciplines.[36] This hypothesis was subsequently expanded after 40 years of investigations and a vast literature has been assembled so far on the athlete's heart, including more recent studies with 3D echocardiography and CMR.[20,37,38] Most sports disciplines are characterized by a varying degree of both isometric and isotonic components, and therefore the original dichotomic classification in strength (isometric) or endurance (isotonic) disciplines is not applicable for most athletes. Therefore, we suggest a simple classification of sports in four major groups based on the main physiologic characteristics of the exercise training: endurance, power, skill, and mixed (*Figure 3*). Pelliccia *et al.*[1] demonstrated that the highest impact on LV mass (with both enlarged LV cavity and increased wall thickness) is associated with some endurance disciplines such as cycling, rowing, swimming, and cross-country skiing, that are all characterized by a high degree of both dynamic and static components. In these athletes the substantial degree of cardiac remodelling shows a close relation to the superior exercise performance (as expressed by maximal oxygen consumption).[39,40] On the other side, predominantly strength disciplines are characterized by only a mild absolute increase in LV wall thickness, which only rarely exceeds the upper range of normalcy.[41] Consequently, LV mass is only mildly increased but, when normalized to athlete's lean body mass, may not be altered.[41–45] This is justified by the fact that strength training consists in short bursts of intensive exercise and pressure overload, but of relatively short cumulative duration. In addition, there are certain disciplines in which the success is mostly based on athlete's technical or bodily skill (skill disciplines) that have only mild cardiovascular demand and characterized by only mild or even absent cardiac adaptations (no significant changes of LV dimensions and mass). Finally, mixed sports are those with alternate phases of work (either dynamic or static exercise) and recovery. Typical examples are the ball and team activities. In such athletes, the cardiac remodelling shows increase in LV cavity and modest change in LV wall thickness and LV mass.

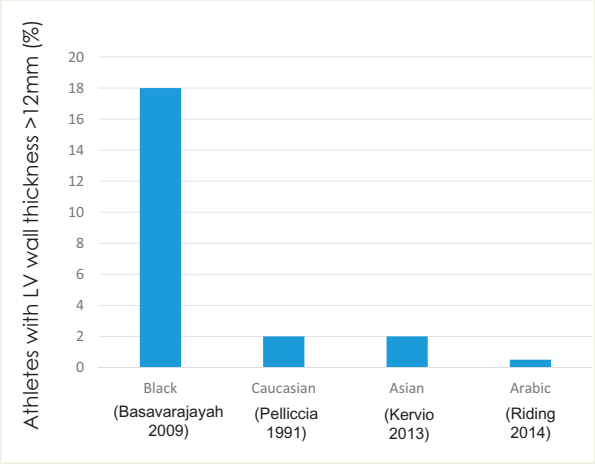

Figure 2 Ethnic-related differences of left ventricular hypertrophy in athletes. The bars represent the percentage of athletes showing left ventricular wall thickness >12 mm on echocardiography in Black, Caucasian, Asian and Arabic ethnicities, respectively.

Recently, Caselli *et al.*[20] demonstrated that regardless of the type of sport participated, the ratio between LV mass and end-diastolic volume remains constant, reflecting the balanced and harmonic remodelling of physiologic LV hypertrophy in most sport disciplines. In clinical practice, the relative wall thickness (calculated as twice the left ventricular posterior wall thickness divided by LV diastolic diameter) may be used to characterize the morphologic remodelling of the left ventricle, with values between 0.30 and 0.45 compatible with physiologic remodelling.[46] Similar adaptations also occur in the other cardiac chambers. The haemodynamic overload caused by endurance training is also responsible for the observed increase in left and right atrial volume and right ventricular size. On the contrary, strength training does not seem to change left atrial (LA) or right ventricular size substantially.[19,47–49] In addition, other data suggest that endurance disciplines are also associated with a significant but mild increase in aortic root dimensions, while power disciplines have only a trivial impact.[50] A practical consequence of these observations is that the heart of an athlete is always characterized by a harmonic and consistent increase in the dimension of all cardiac chambers, while a non-harmonic (disproportionate) remodelling potentially suggests a non-physiologic process.

Finally, in the presence of unusual or disproportionate cardiac remodelling in relation to the sport participated and described physiologic determinants, the potential impact of doping substances

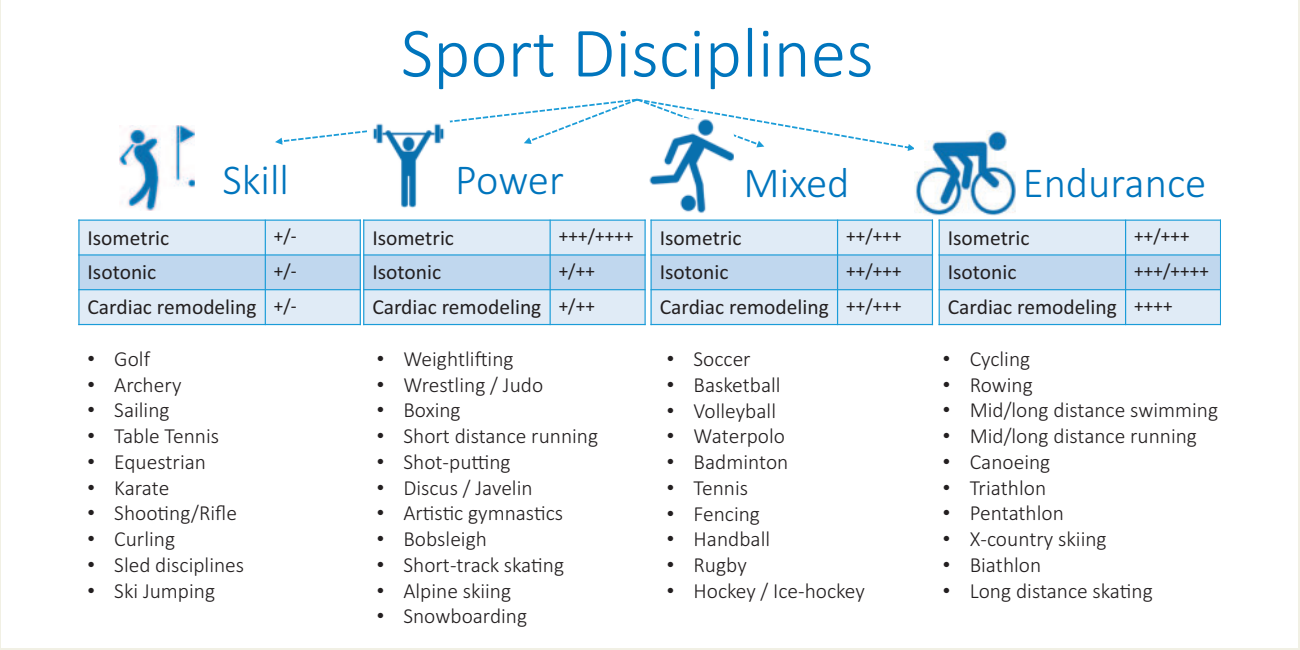

Figure 3 Simplified classification of the most common Olympic sport disciplines, according to the relative isometric and isotonic components of exercise and resulting cardiovascular adaptation.

(mostly anabolic androgenic hormones, peptide hormones, growth factors, erythropoietin or its derived, and stimulants) should always be considered.[8,42,43,51–53] A list of banned drugs is reported and annually updated by the World Anti-Doping Agency. However, in this setting, scientific evidence is lacking (because of the concealed use of the drugs and obvious clinical and ethical limitations to perform a controlled study) and only inconsistent and circumstantial observations have been reported so far. Most of the informations are limited to anabolic androgenic hormones. Few studies demonstrated that power athletes using these hormones typically show concentric LV hypertrophy compared with non-user athletes.[42,43,53–55] Specifically, anabolic androgenic steroids stimulate cellular protein synthesis and promote the growth of all organs, including the heart; cardiac effects can include the development of concentric hypertrophy and myocardial fibrosis which can persist after deconditioning and years after discontinuation of drug abuse.[51,56] On cardiac imaging, concentric hypertrophy and impaired systolic and diastolic LV function, which are typically not present in non-user athletes, are suspicious for drug abuse.[54,55] Anabolic androgenic hormones users have shown a higher mortality compared with clean athletes and postmortem studies confirmed the existence of a drug-induced cardiomyopathy, characterized by greater cardiac mass, increased left ventricular wall thickness, and a large prevalence of extracellular fibrosis.[51,57,58]

3. Indications for imaging testing and normal findings in athletes

3.1 Clinical and electrocardiogram abnormalities requiring cardiac imaging

Cardiovascular imaging usually represents an advanced step of athlete's evaluation and is preceded by physical examination and/or 12-leads ECG. *Table 1* shows the most important clinical indications to perform cardiovascular imaging in athletes. The ability to make diagnosis of an abnormal cardiovascular condition in athletes mainly depends on the clear understanding of the clinical context, on the knowledge of the physiologic limits of cardiac adaptations, and on being able to seek those conditions that are at potential risk for cardiac arrest/sudden death (SCD) or adverse cardiac outcome. Most of the cardiovascular diseases observed in athletes may be suspected on the basis of an abnormal ECG (with the remarkable exception of coronary artery disease (CAD)/anomalies and valvular heart disease). Thanks to the large amount of data collected over the last decade, our understanding and interpretation of the athlete's ECG has evolved and contemporary criteria have reduced the false positives, improving the diagnostic efficacy. Specifically, after the initial work by Corrado *et al.* in 2010, new refined criteria for ECG interpretation have been subsequently published.[16,26,59,60] These refined criteria demonstrated to improve specificity up to 84% in black athletes and 94% in white athletes, without compromising the sensitivity of ECG in detecting major cardiac pathologies (100%).[26]

According to contemporary recommendations for interpretation of the athlete's ECG, the ECG abnormalities are divided in three groups according to their prevalence, relation to exercise training, association with an increased cardiovascular risk, and need for further clinical investigation to confirm (or exclude) presence of underlying cardiovascular disease.[59] The athlete's heart is commonly (up to 80%) associated with ECG changes such as sinus bradycardia, first-degree AV block, and early repolarization resulting from physiologic adaptation of the cardiac autonomic nervous system to training, i.e. increased vagal tone and/or reduced sympathetic activity. Moreover, the ECG of trained athletes often exhibits pure voltage criteria for LV hypertrophy that reflect the physiological LV remodelling, consisting of increased LV wall thickness and chamber size. Although these

Table 1 Clinical indications to perform cardiovascular imaging studies in athletes

Clinical history:	Imaging tests of choice	Heart disease	Additional testing
SCD in the family	Echocardiography	Cardiomyopathies	Clinical and genetic family screening in selected cases
Known cardiomyopathy in the family	CMR	Mitral valve prolapse	
Palpitations	Echocardiography	Cardiomyopathies	Consider 24-h and/or long-term ambulatory ECG monitoring and/or electrophysiological study in selected cases
Syncope	CMR	Coronary artery disease/ anomalies	CT according to clinical suspicion Consider stress echo to rule out LV outflow obstruction
Chest pain	Echocardiography	Coronary artery disease/ anomalies	Consider the risk profile, age and radiation exposure
	CMR CT Nuclear imaging		Consider exercise stress imaging
Physical examination	**Imaging tests of choice**	**Heart disease**	**Additional testing**
Cardiac murmurs Abnormal cardiac sound	Echocardiography	Valvular heart disease Congenital heart defects	Additional tests on the basis of echocardiographic findings and clinical suspicion (e.g. CMR)
Marfanoid habitus	Echocardiography CT CMR	Marfan disease	Clinical and genetic family screening Accurate evaluation of thoracic aorta
12-leads electrocardiogram	**Imaging tests of choice**	**Heart disease**	**Additional testing**
T-wave inversion	Echocardiogram CMR	Cardiomyopathies Myocarditis	Clinical and genetic family screening Annual follow-up with imaging tests in athletes with normal findings at initial evaluation
ST-segment depression	Echocardiogram CMR	Cardiomyopathies Myocarditis Coronary artery disease Valve disease	Consider exercise stress imaging Coronary CT or nuclear imaging in athletes with clinical suspicion of coronary artery disease
Pathologic Q-waves	Echocardiogram CMR	Cardiomyopathies Myocarditis Coronary artery disease	Consider exercise stress imaging Coronary CT or nuclear imaging in athletes with clinical suspicion of coronary artery disease
Complete LBBB	Echocardiogram CMR CT Nuclear imaging	Cardiomyopathies Myocarditis Cardiac sarcoidosis Valve disease Coronary artery disease/ anomalies	Comprehensive cardiac evaluation for exclusion of heart disease Consider exercise stress imaging
Bifascicular block (RBBB and left anterior hemiblock)	Echocardiogram	Cardiomyopathies Myocarditis Cardiac sarcoidosis Coronary artery disease	Additional tests on the basis of echocardiographic findings and clinical suspicion
Non-specific intraventricular conduction delay	Echocardiogram	Cardiomyopathies Coronary artery disease/ anomalies	Additional tests on the basis of echocardiographic findings and clinical suspicion
Minor non-voltage criteria for LV or RV hypertrophy (atrial enlargement and QRS axis deviation)	Echocardiogram	Cardiomyopathies Valve disease Congenital heart disease Pulmonary hypertension	Additional tests on the basis of echocardiographic findings and clinical suspicion
Abnormal exercise testing (repolarization abnormalities/ symptoms/arrhythmias)	Echocardiography	Coronary artery disease/ anomalies	Consider the cardiovascular risk profile and age
	CMR		Consider also exercise stress imaging
	CT Nuclear imaging	Cardiomyopathies Myocarditis	Low-radiation examinations advised in young individuals

CMR, cardiac magnetic resonance; CT, computed tomography; LBBB, left bundle branch block; LV, left ventricle; RBBB, right bundle branch block; RV, right ventricle; SCD, sudden cardiac death.

ECG changes (i.e. training related) may be considered 'abnormal', they do not imply the presence of cardiovascular disorders or an increased cardiovascular risk in the athlete. These ECG abnormalities should be clearly separated from training unrelated ECG patterns (present in <5%), such as ST-segment depression and T-wave inversion, pathologic Q waves, major intraventricular conduction defects, ventricular pre-excitation, long or short QT interval, and ventricular arrhythmias, which may be an expression of cardiovascular disorders, notably cardiomyopathies and cardiac ion channel diseases, with potential risk of SCD during sports.

Finally some borderline ECG variants (left and right atrial enlargement, left and right axis deviation, and right ventricular hypertrophy) are considered of uncertain significance in athletes and, in the setting of cardiac evaluation, should not require additional investigation if not associated with positive family history and present in isolation.[26]

The ECG should be evaluated in relation with the athlete's gender, age and race, family history of cardiovascular disease and/or SCD, clinical symptoms, physical examination, and intensity/duration of physical exercise. In asymptomatic athletes with a negative family history, ECG changes due to cardiac adaptation to physical exertion should not cause alarm and do not represent indication for additional evaluation. Further diagnostic work-up, instead, should be reserved to the limited subset of athletes with ECG changes potentially reflecting underlying heart disease.

Genotype–phenotype correlation studies in cardiomyopathies reveal that ECG abnormalities may represent the only sign of disease expression in mutation carriers in the absence of any morphologic typical features and even before structural changes in the heart may become evident. Abnormal ECG repolarization in young and apparently healthy athletes may represent initial expression of underlying cardiomyopathy that may not be evident until many years later and that may ultimately be associated with adverse outcomes. The observation that T-wave inversion may identify subjects at risk of subsequent development of structural heart disease underscores the importance of continued clinical surveillance and follow-up. We suggest that athletes with repolarization abnormalities, even in the absence of structural heart disease at first evaluation (after comprehensive and multi-modality imaging), should have imaging studies on a regular basis; usually echocardiography is sufficient on annual basis but when images are suboptimal, other imaging modalities should be considered.[61]

3.2 Echocardiography

Standard echocardiography helps to define the upper limits of athlete's LV hypertrophy. In a reference study of 1309 athletes, 55% had an increased LV end-diastolic diameter and, of interest 14% had an LV end-diastolic diameter >60 mm (mostly endurance athletes) in the presence of normal ejection fraction (EF) and normal or increased stroke volume (*Table 2*). Left ventricular size should therefore be considered in the context of exercise capacity, given its robust association with VO_2 max.[1,40] Left ventricular cavity is also strongly related to body size, therefore scaling measurements to BSA is advised in the clinical practice (upper limits in athletes have been reported as: <35 mm/m^2 in male and 40 mm/m^2 in female).[4]

Maximal LV wall thickness is <12 mm in the majority of Caucasian athletes, with only 2% ranging from 13 to 16 mm, and none >16 mm.[1,62] Septal wall thickness is thinner in women (average = 9 mm, upper limit = 11 mm) than in men of the same age and body size.[63] Conversely, in black athletes LV hypertrophy (LV wall thickness ≥13 mm) is detected in 18% of males and (LV wall thickness > 11 mm) in 3% of females[23,64] (*Table 2*; *Figure 2*).

In adolescent athletes, LV end-diastolic diameter and LV wall thickness exceed values of age- and sex-matched sedentary controls, but are lower than those of adult athletes (LV end-diastolic diameter <60 mm; LV wall thickness <11 mm).[65]

Most of the adaptations induced by physical training seem to regress after temporary training suspension (deconditioning) of only few weeks (9–12), while LV dilatation persists in 20% of the cases, even after an average of 5 years of inactivity, without eliciting adverse cardiovascular events during the follow-up.[66]

Left ventricular ejection fraction is usually unchanged in athletes. Several studies and a meta-analysis confirmed that LV function in athletes is not different from untrained subjects and EF is consistently 50%; therefore, the finding of a reduced EF (<50%) cannot be considered uniquely as a benign consequence of athletic training and deserves careful clinical investigation.[20,67]

With regard to diastolic function, transmitral pulse wave Doppler inflow pattern demonstrates a normal pattern, with an increased contribution of early filling velocity at rest (*E/A* ratio >2)[68,69] (*Figure 4*). Pulsed tissue Doppler imaging (TDI) provides additional information showing normal *s′* peak velocity at rest (>8 cm/s) and *e′* peak velocity of the mitral annulus (>10 cm/s).[68,70,71] Conversely, individuals with mild morphological expression of HCM exhibit lower *e′* velocity compared with athletes.[5] The full spectrum of systolic and diastolic myocardial velocities has been described in large populations of competitive athletes.[68,72]

Left atrial enlargement is common in large cohorts of athletes, proportional to biventricular enlargement and affected by the type of training. Pelliccia *et al.*[19] reported a mild increase of LA diameter (≥40 mm) in 18% and a marked LA dilatation (≥45 mm) in 2% of the athletes. Left atrial volume is the preferred method for the assessment of LA remodelling and D'Andrea *et al.* confirmed a mild enlargement by using LA volume index (LAVi ≥ 34 mL/m^2) in 24% and moderate enlargement in 3% of athletes.[48,73]

Elite athletes have normal aortic root diameter measured at the sinus of Valsalva and aortic valve annulus, with <1% of athletes showing increased dimensions. Clinicians evaluating athletes should therefore know that marked aortic root dilatation represents a pathological process and not a physiological adaptation to exercise.[50,74,75]

Right atrium and right ventricle (RV) also undergo structural and functional remodelling as a result of haemodynamic challenges of exercise training.[76] Endurance sport requires very high cardiac outputs to be sustained for long periods and, as a result, the right heart undergoes substantial remodelling.[29,47,76–78] A physiological RV enlargement (usually proportional with LV enlargement) was observed in both black and white athletes (*Table 3*).[18] Despite significant RV enlargement, athletes usually show normal RV systolic function, without significant differences compared with untrained subjects.[76,79] Only a small minority may present a mildly reduced RV fractional area change[76]; ambiguities in the interpretation of mildly reduced RV function may be resolved by assessing RV function during exercise inducing both pressure and volume overload.[80,81]

Exercise stress echocardiography can be considered a very reliable and non-invasive methodology to provide information on cardiac

Table 2 Athlete's left heart morphologic and functional parameters including upper or lower limits

First author	Year	No. of athletes	Type of sport	Parameter	Gender	Mean value	Cut-off value
Pelliccia	1999	1309	S P M E	LV End diastolic diameter (mm)	♂	55	70
Whyte	2004	442	P E	LV End diastolic diameter (mm)	♀	49	65
Pelliccia	1996	600	S P M E	LV End diastolic diameter (mm)	♀	49	66
Makan	2005	900	E	LV End diastolic diameter (mm)	♂ and ♀ Adolescent	51	60
Spirito	1994	947	S P M E	LV wall thickness (mm)	♂	10	16
Rawlins	2010	440	P E	LV wall thickness (mm)	♀ Black	9.5	13
Sharma	2002	720	P E	LV wall thickness (adolescent) (mm)	♂ and ♀ Adolescent	9.5	12
Basavarajaiah	2008	300	P E	LV wall thickness (black athletes) (mm)	♂ Black	11.5	16
Caselli	2015	1145	S P M E	LV mass/BSA (g/m^2)	♂ and ♀	103	146
Finocchiaro	2016	1083	P M E	LV mass/BSA (g/m^2)	♂	83	117
					♀	101	143
Pelliccia	2005	1777	S P M E	LA antero-posterior diameter (mm)	♂	37	50
					♀	32	45
D'Andrea	2010	650	P E	LA volume index (mL/m^2)	♂	28	36
					♀	26.5	33
Pelliccia	2010	2317	P E	Aortic toot diameter (mm)	♂	32	40
					♀	28	34
D'Andrea	2010	615	P E	Proximal ascending aorta (mm)	♂ and ♀	28	34
Caselli	2015	1145	S P M E	LV ejection fraction (%)	♂ and ♀	64	55
				E/*A*		1.93	1.3
				TDI *e*′ septal (cm/s)		13.8	10.3
				TDI *e*′/*a*′ septal (cm/s)		2.04	1.23
				E/*e*′ septal		6.4	8.5
D'Andrea	2010	650	P E	TDI *s*′ septal (cm/s)	♂ and ♀	13	8
				TDI *e*′ septal (cm/s)		24	10
				TDI *s*′ lateral (cm/s)		15	9
				TDI *e*′ lateral (cm/s)		16	11
				TDI *e*′/*a*′ lateral		1.45	1.2
D'Andrea	2006	155	P	LV Intra-ventricular delay (ms)	♂ and ♀	9.5	45

BSA, body surface area; LA, left atrium; LV, left ventricle; TDI, tissue Doppler imaging. Type of sport: S, skill; P, power; M, mixed; E, endurance. ♀, female; ♂, male.

function, contractile reserve, exercise capabilities, and arrhythmias, which can be combined with clinical and ECG data and contribute to detect cardiac abnormalities. Being a safe and well-tolerated test, it is generally better accepted than pharmacological stress by individual athletes.[8,82] Typical indication of exercise echocardiography is the evaluation of global and regional cardiac function during exercise in cases of suspect CAD or anomalies, in individuals with chest pain symptoms, abnormal ECG or doubtful ECG stress test. In some elite endurance athletes, both LV and RV dilatation has been reported to be associated with a mild impairment of systolic function. In these cases, exercise echocardiography enables the assessment of contractile reserve of the dilated ventricles, with a significant improvement in contractility during physical exertion, suggesting a physiological response.[8,80,82] Finally, a special mention deserve the evaluation of athletes with valvular heart disease (i.e. haemodynamically significant valvular regurgitation, BAV, and mitral valve prolapse); in these cases exercise echocardiography may give complementary information on exercise tolerance, biventricular contractile reserve, and changes of haemodynamic and valvular functional parameters (such as valvular gradients, regurgitations, pulmonary artery pressure, and diastolic function).[82]

3.3 Novel echocardiographic techniques

Speckle tracking (STE) and 3D echocardiography are not part of the routine evaluation of the athlete, but may become useful in specific circumstances to clarify the nature of cardiovascular adaptations. The indications to complete a routine echocardiographic examination in an athlete with these advanced technologies are summarized in *Table 4*.

Left ventricular global longitudinal strain (GLS) obtained by STE is currently the most used parameter in clinical practice. Main echocardiographic studies using 2 STE in the athlete's heart are summarized in *Table 5*. These studies demonstrate that a reduction in LV GLS is an uncommon feature in athlete's heart and cannot be considered a physiological adaptation to training. The current normal value for the general population varied from -16% to -22%, mean -20%.[83,84] Similar values have been found in athletes, suggesting that a measure <15% should raise the suspicion of an underlying myocardial disease, particularly in case of other concomitant subclinical anomalies (*Figure 5*).[83–89]

Speckle tracking echocardiography has been recently applied to the investigation of the RV in athletes, providing new insights into the mechanisms of its physiologic remodelling and the assessment of the

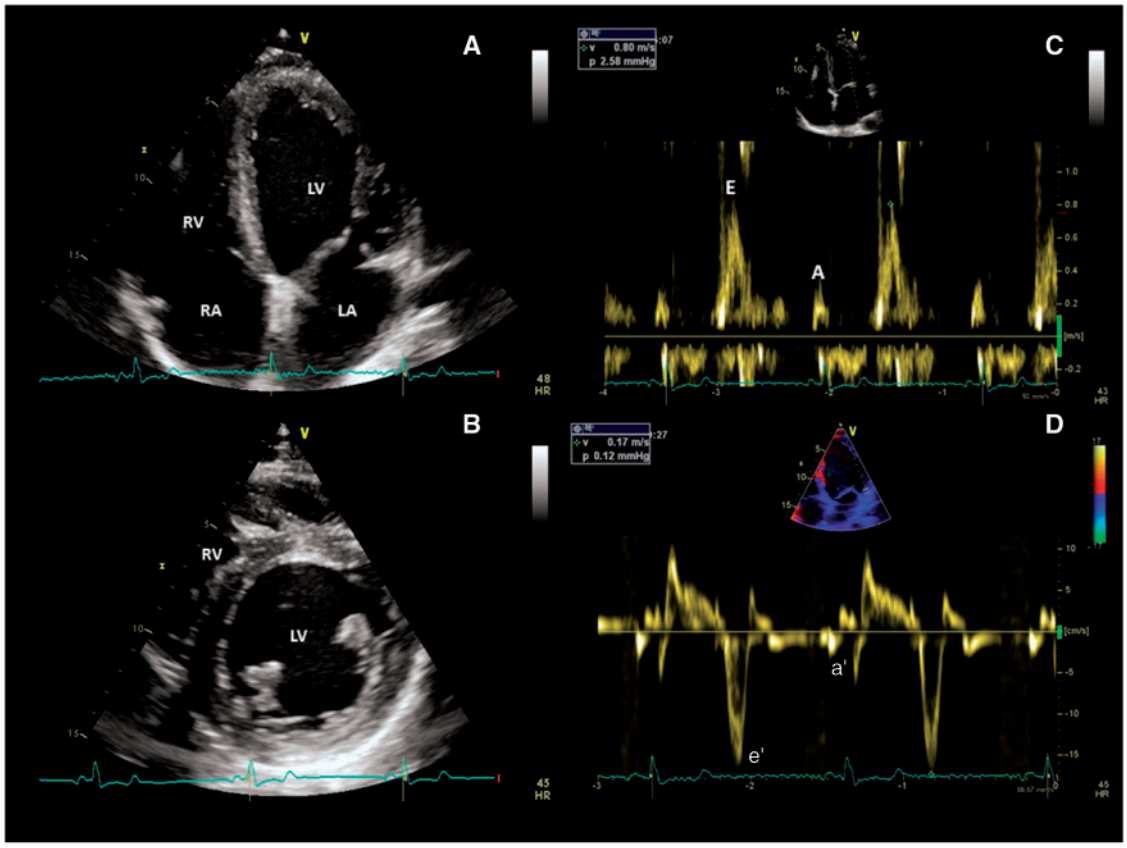

Figure 4 Twenty-two years-old male competitive endurance athlete (swimmer). Panel A: Apical 4-chamber and (Panel B) parasternal short-axis views, showing left ventricular (LV) hypertrophy, with symmetric increase of both wall thickness and LV internal cavity diameters. Panel C: Standard Doppler transmitral inflow pattern, showing a 'supranormal' early-diastolic function, with increased E velocity and E/A ratio. Panel D: Pulsed Tissue Doppler pattern of LV lateral wall, highlighting the enhanced early-diastolic myocardial function, i.e. increased e' velocity. LA, left atrium; LV, left ventricle; RA, right atrium; RV, right ventricle.

possible detrimental effects of strenuous and chronic exercise training on RV function, particularly in endurance athletes.[33,49,90–96] Strain and strain rate imaging, being able to objectively quantify regional RV dysfunction, have demonstrated to improve the ability to diagnose AC and to distinguish between physiology and pathology.[33,97,98] However, studies investigating RV function in athletes by STE remain limited and there is lack of universally accepted cut-off values (*Table 5*).

Three-dimensional echocardiography has added quantitative information on the assessment of the athlete's heart, indeed cardiac volumes and mass can be estimated more precisely without the use of geometric assumptions and with very fast acquisition times.[99–101] Three-dimensional derived information on LV geometry are very close to those obtained by CMR while 2D echocardiography routinely underestimates these measurements.[99,102] The geometric pattern of LV adaptation to different training protocols have been investigated with 3D echocardiography. In athletes, regardless to the sport discipline, a balanced ratio between LV mass and end-diastolic volume has been described by 3D echocardiography as opposed to what typically occurs in cardiomyopathies.[20,102,103] Additionally, the distribution of hypertrophy within the LV has been further investigated by the mass dispersion index (MDI; the standard deviation of segmental LV mass) which is able to differentiate the homogeneous segmental distribution of LV mass typical of athletes or hypertensive patients compared with the non-homogeneous hypertrophy which is usually expression of HCM.[104]

3.4 Cardiac magnetic resonance

Due to its diagnostic versatility, CMR imaging represents the second most valuable imaging method in the routine screening of active athletes and has definitely a role in the assessment of suspected cardiac disease. Studies reporting the systematic use of CMR as screening tool for cardiac abnormalities in athletes are, so far, scant and none have reported malignant arrhythmias or SCD as outcomes related to CMR findings.[105–107] Additionally, it is worthy to consider that CMR shows systematically larger atrial and ventricular dimensions and volumes, and smaller wall thickness and mass, compared with echocardiography.[108] Therefore it should be advised to use some caution in applying echocardiographic derived reference values when performing CMR in athletes.

The main diagnoses relevant for a CMR study are: HCM, DCM, AC, LVNC, BAV, aortic root diseases, myocarditis, pericarditis, and ischaemic heart disease (see specific paragraphs). *Figure 6* describes the main patterns of relevant diseases associated with risk of SCD in

Table 3 Athlete's right heart morphologic and functional parameters including upper or lower limits

First author	Year	No. of athletes	Type of sport	Parameter	Gender	Mean value	Cut-off value
D'Andrea	2013	650	P E	RV diameter basal (mm)	♂	43.5	55
					♀	39	49
				RV diameter middle-ventricle (mm)	♂	34	47
					♀	32	43
				RV longitudinal diameter (base-to-apex; mm)	♂	89	109
					♀	82	100
Zaidi	2013	675	P E	RVOT proximal (mm)	♂	32	43
					♀	30	40
				RVOT distal mm	♂	23.5	32
					♀	21.5	29
Zaidi	2013	675	E	RA area (cm^2/m^2)	♂	19.5	28
					♀	15.5	24
D'Andrea	2011	650	P E	PASP (mmHg)	♂ and ♀	24	40
D'Andrea	2013	650	P E	TAPSE (cm)	♂ and ♀	2.1	2.0
				RV FAC (%)		48.5	47
Oxborough	2012	102	E	RV TDI s′ (cm/s)	♂ and ♀	11	8
				RV TDI e′ (cm/s)		10	6
D'Ascenzi	2016	1009	S P M E	RVOT proximal (mm)	♂	28.4	34
				RVOT proximal index (mm/m^2)	♀	26.1	32
					♂	14.4	18
					♀	15.3	19
				RVOT distal (mm)	♂	29.8	16
				RVOT distal index (mm/m^2)	♀	27.3	34
					♂	15	19
					♀	15.9	21
				RV diameter basal (mm)	♂	40.6	49
					♀	35.2	44
				RV diameter middle ventricle (mm)	♂	27.3	35
					♀	23.9	31
				RV diastolic area (cm^2) (male)	♂	25.1	33
					♀	19.3	27
				RV systolic area (cm^2) (male)	♂	12.1	18
					♀	9.0	14
				TAPSE (mm) (male)	♂ and ♀	24	19
				RA area (cm^2) (male)	♂	18.9	25
					♀	14.8	20
				s′ (cm/s)	♂	14.8	12
					♀	14.2	11
				RV FAC (%)	♂	52.0	39
					♀	53.4	38

FAC, fractional area change; RA, right atrium; PASP, pulmonary artery systolic pressure; RV, right ventricle; RVOT, right ventricular outflow tract; TDI, tissue Doppler imaging; TAPSE, tricuspid anulus peak systolic excursion. Type of sport: S, skill; P, power; M, mixed; E, endurance. ♀, female; ♂, male.

athletes in a stepwise selection decisional algorithm using CMR findings after the whole patient's data (including symptoms, personal and familial history, electrocardiography, and echocardiography) have been interrogated.

Protocols include multiplanar cine CMR to assess morphology and function of all valves, especially the aortic valve and root whose anomalies can lead to SCD. Most importantly, cine CMR evaluates heart chambers volume and mass accurately and with high reproducibility, and is considered the standard of reference for the assessment of global and regional contractile function.[39,109,110]

Assessment of the RV volume, shape, and ejection fraction (EF) are main CMR criteria recognized by the task force for imaging diagnosis of AC,[111,112] although involvement of the LV may also occur.[113] The dependence of the size of the RV to the gender and the BSA highlights the need for indexing the RV parameters to the BSA. Indeed, RV remodelling and enlargement are normal adaptations to

Table 4 Indication to complete the routine echocardiographic evaluation by speckle-tracking or by 3D echocardiography

Indications for speckle-tracking echocardiography
• Identification of pre-clinical anomalies useful to the differential diagnosis between athlete's heart and early DCM (LV)
• Identification of pre-clinical anomalies useful to the differential diagnosis between athlete's heart and early HCM (LV)
• Characterization of regional wall motion abnormalities (LV and RV)
Indications for 3D echocardiography
• Better assessment of LV volumes and function
• Assessment of pattern of LV geometry
• Quantification of the extent of LV trabeculation

DCM, dilated cardiomyopathy; HCM, hypertrophic cardiomyopathy; LV, left ventricle; RV, right ventricle.

Table 5 Most relevant studies assessing left (upper panel) and right (lower panel) ventricular strain by speckle-tracking echocardiography in athletes

Author	Year	Sport discipline	Nr	Longitudinal strain
				Left ventricle
Caselli *et al.*	2014	Olympic athletes	200	-18.1 ± 2.2%
Nottin *et al.*	2008	Elite cyclists	16	19.2 ± 1.9%
Cappelli *et al.*	2010	Endurance athletes	50	-18.4 ± 3.0%
Galderisi *et al.*	2010	Top level rowers	22	-22.2 ± 2.7%
Simsek *et al.*	2913	Marathon runners	22	-22.3 ± 2.2% (global)
Simsek *et al.*	2013	Wrestlers	24	-21.8 ± 1.7% (global)
Weiner *et al.*	2013	University Rowers	15	-16.8 ± 2.1% (pre-training)
				-18.3 ± 2.8% (post-training)
				Right ventricle
Teske *et al.*	2009	Endurance athletes/Olympic endurance athletes	58/63	-28.5 ± 2.9%/
				-27.6 ± 3.1%
Oxborough *et al.*	2012	Endurance athletes	102	-27.0 ± 6.0%
Pagourelias *et al.*	2013	Endurance/Power athletes	80/28	-23.1 ± 3.7%/
				-25.1 ± 3.2%
Esposito *et al.*	2014	Top level rowers	40	-26.3 ± 3.6% (global)
				-29.1 ± 4.1% (free wall)
D'Ascenzi *et al.*	2015	Mixed sport disciplines	29	-28.7 ± 4.9% (Pre-season)
				-29.2 ± 4.1% (Mid-season)
				-30.0 ± 3.7% (End-season)

training in amateurs and endurance athletes.[114,115] Therefore, we recommend that RV enlargement is defined only when end-diastolic volume exceeds the major diagnostic criteria in the athletic population (i.e. ≥110 mL/m^2 for male and ≥100 mL/m^2 for males).[111] As the systolic function of the RV is usually normal in athletes, both major (RVEF <40%) and minor (RVEF < 45%) criteria should be considered in the differential diagnosis.[111]

Assessment of LV hypertrophy or dilatation using cine CMR also provides paramount diagnostic information. Diagnosis of HCM is likely when myocardial hypertrophy has a focal distribution.[116] Hypertrophic cardiomyopathy may nevertheless display a diffuse pattern, difficult to differentiate from that occurring in certain hypertensive individuals and normal athletes (especially Afro-Caribbean males).[24,62]

Cardiac magnetic resonance is also considered as the superior method for fibrosis imaging. The assessment of late gadolinium enhancement (LGE) has excellent ability to outline myocardial replacement fibrosis and is commonly used in detection of myocardial scar and workup of cardiomyopathies,[117–119] and differentiation between diseased and adaptive athletes, even though small spots of fibrosis have been occasionally reported in endurance athletes without other obvious disease.[120]

Myocardial fibrosis can be characterized by typical ischaemic and non-ischaemic patterns, with the latter including several subpatterns with the potential to sharpen the differences between myocardial diseases. For example, in diffuse LV hypertrophy, LGE helps distinguishing potentially adaptive changes from diseases, among which the most common is HCM (especially in the absence of LV overload)

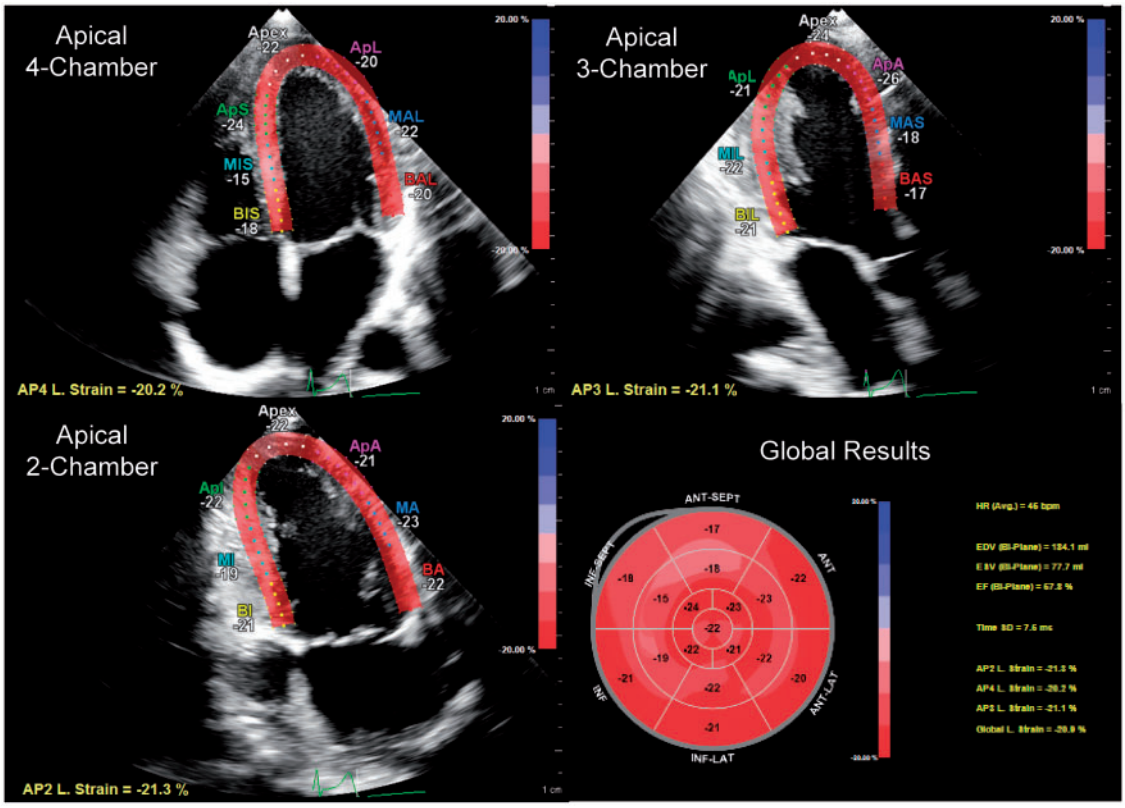

Figure 5 Left ventricular strain assessed by 2-dimensional speckle tracking echocardiography in a 20 year-old male soccer player. Global and regional longitudinal deformation is assessed from apical 4-, 3- and 2-chamber views. Peak regional values are depicted in the bull's eye plot in the lower right panel. The global longitudinal strain (GLS) is -20% (in the range of normality).

where LGE is typically patchy or confluent and occurs at the RV insertion.[121–123] In normal-sized hearts, common non-ischaemic LGE patterns involve the mid-wall and the subepicardium, figuring inflammatory disease-related necrosis or scars (myocarditis, sarcoidosis, and collagen vascular diseases), while in dilated LV presence of LGE suggests acute or subacute inflammatory diseases like DCM or predominant left-sided AC. Rare diseases should however, be considered in LV hypertrophy,[124–128] and even other heart shapes when the LGE pattern is atypical. Indeed, diffuse subendocardial, subepicardial basal, and intramyocardial LGE have respectively been reported in amyloidosis, Anderson-Fabry disease, and mitochondrial myopathy.[129,130]

T1 mapping is a very promising CMR method for the assessment of the extracellular volume and diffuse fibrosis. This technique can potentially be important in myocardial diseases where LGE is less sensitive.[131] Indeed, the myocardial T1 values tend to increase with the amount of extracellular matrix and aging,[132] and decrease with fatty infiltration such as in Anderson-Fabry disease.[133,134]

3.5 *Computed tomography*

Cardiac CT is characterized by a high-spatial resolution and short-scan times, but limited temporal resolution, making the technique ideal for high-resolution angiography. However before the indication to CT scan, a due consideration concerns the radiation exposure[135]; indeed, radiation dose of cardiac CT depends on the scanner type, scan protocol, and the efforts taken to limit exposure. Dynamic evaluations using older scanners can result in doses exceeding 20 mSv, while CT coronary angiography requires nowadays no more than 1 mSv in properly prepared patients using modern CT technology.[136] Although many aspects of cardiac disease can be visualized well, cardiac CT cannot be the first-choice imaging modality in young athletes. Therefore, cardiac CT should be reserved for individuals with suspected CAD (symptoms of angina, positive exercise test, arrhythmias, or syncope during exercise), aortic diseases, or pericardial pathology (*Table 6*). Cardiac CT is the most accurate technique for imaging anomalous coronary anatomy, including intramural course. The point of origin, course, adjacent structures, and termination (fistulas) can be evaluated (*Figure 7*). However, morphology is often not sufficient for interpretation of the pathophysiological relevance. Obstructive coronary disease can be excluded in case of suspected myocardial ischaemia.

Cardiac CT can also visualize most morphological features of the different cardiomyopathies, including ventricular wall dimensions and structure, cavity sizes, global contractile function, and even regional wall motion abnormalities.[137,138] However, although cardiac CT very accurately measures global ventricular function, its practical use is limited by the radiation exposure,[139] hence, echocardiography and CMR are preferred. In case of suboptimal echocardiographic images and contraindications to CMR, CT scan may represent the alternative imaging modality.

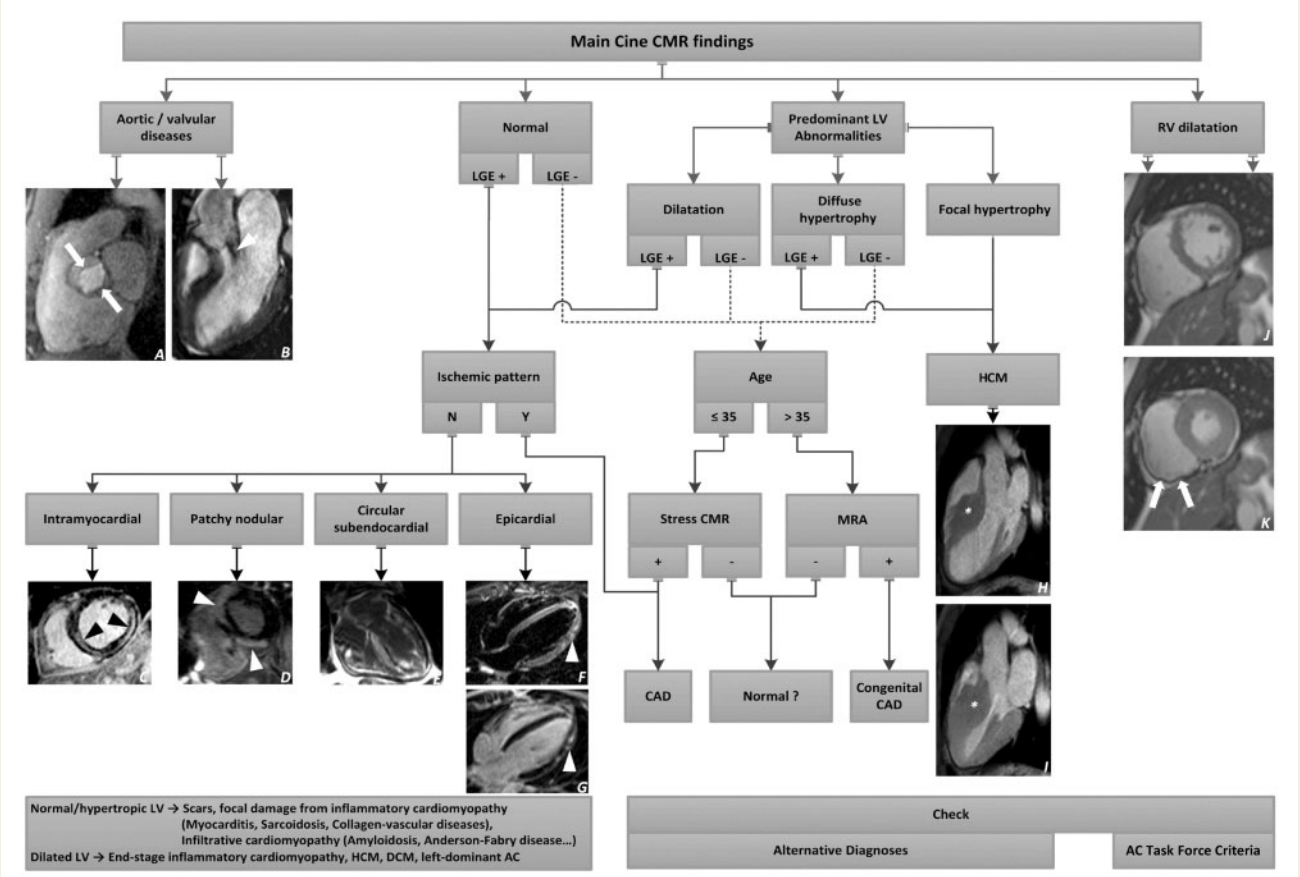

Figure 6 Stepwise diagnostic algorithm involving Cardiac Magnetic Resonance (CMR) with inserts illustrating common diseases at risk for Sudden Cardiac Death (SCD). CMR is usually performed as a second level cardiovascular examination. The first step examines cine images in order to demonstrate/exclude aortic valve and root diseases (A and B are respectively end-diastolic transverse aortic and 3-chamber views displaying bicuspid aortic (arrows) valve with regurgitation (arrowhead) and eccentric left ventricular (LV) hypertrophy, right ventricular (RV) dilatation and predominantly LV abnormalities. In case of RV dilatation, task force CMR criteria for the diagnosis of Arrythmogenic Cardiomyopathy (AC) should be checked (J and K inserts are respectively end-diastolic and end-systolic short-axis cine views of a patient with recent onset of tachyarrhythmia, showing enlarged RV (end-diastolic volume = 115 ml/m^2) and dyskinetic segments in the inferior wall (arrows). The diagnosis of hypertrophic cardiomyopathy (HCM) is usually straightforward with focal LV hypertrophy (H and I inserts respectively represent end-diastolic and end-systolic 3-chamber cine views, showing septal LV hypertrophy (asterisks). Late gadolinium enhancement (LGE) images are the next clue to the diagnosis in the remaining cases (C-G inserts represent typical patterns of non-ischemic LGE on short-axis and 4-chamber views (arrowheads). These patterns are associated to either disease-related focal myocardial damage or scar in normal-shaped LV, whereas they represent diffuse damage or end-stage cardiomyopathies when the LV is dilated. When both cine CMR and LGE patterns are normal, coronary artery disease (CAD) can be excluded using Magnetic Resonance Angiography (MRA) or stress CMR with respect to the patient age. AC, arrhythmogenic cardiomyopathy; CAD, coronary artery disease; CMR, cardiac magnetic resonance; HCM, hypertrophic cardiomyopathy; LGE, late gadolinium enhancement; LV, left ventricle; MRA, magnetic resonance angiography; N, No; RV, right ventricle; Y, Yes.

Table 6 Indications to perform coronary computed tomography based on symptoms and age. Low-radiation examinations advised in young individuals

Age category	Suspect coronary artery disease	Indication to perform CT coronary angiography
Young (<35 years)	Coronary artery anomalies (origin, course)	• Syncope • Major ventricular arrhythmias induced by exercise • Positive exercise test
Adults (>35 years)	Atherosclerotic coronary artery disease	• High risk profile • Atypical chest pain • Borderline exercise testing

CT, computed tomography.

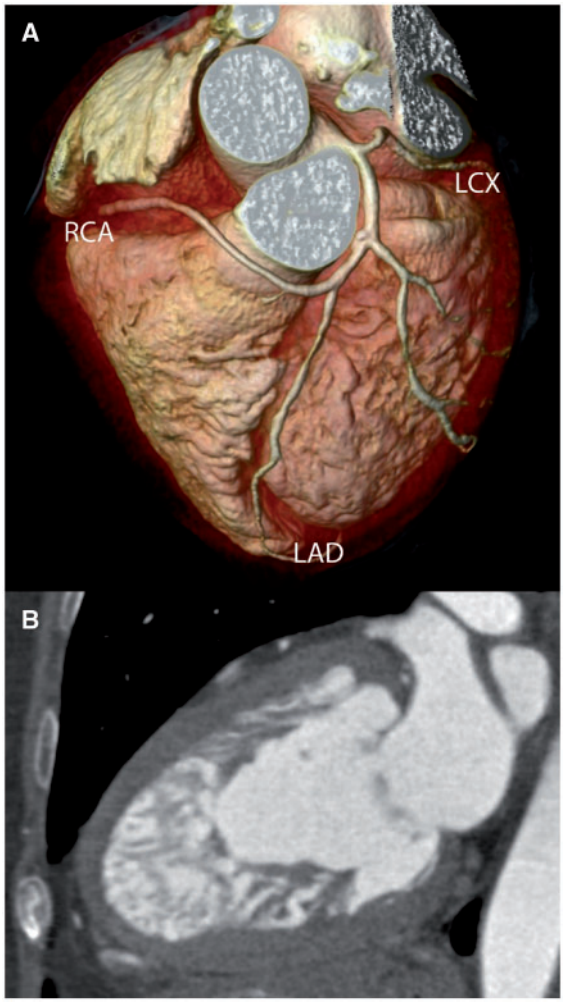

Figure 7 Cardiac Computed Tomography (CT) imaging of a patient with non-compaction cardiomyopathy (B) as well as a single coronary artery (A). LAD, left anterior descending artery; LCX, left circumflex artery; RCA, right coronary artery.

Left-sided valve morphology can be assessed well, while CT imaging of the right-sided valves is more challenging and requires specific attention to contrast timing. Cardiac CT offers no flow-based functional evaluation. Planimetry of stenotic valve areas has been described.[140] Pericardial thickening and calcification are well visualized by cardiac CT, and pericardial fluid contents may to a degree be differentiated by CT attenuation values. Finally, while cardiac CT may be considered the clinical standard for aortic imaging, 3D CMR angiography with or without contrast agent application is also of high-diagnostic value and can easily be integrated in a single session CMR examination.

3.6 *Nuclear imaging*

Both photon emission computed tomography (SPECT) or positron emission tomography (PET) can be used in athletes for the assessment of myocardial ischaemia when coronary artery anomalies or disease are suspected, however ischaemia can also be related to dysbalanced myocardial perfusion (e.g. in severe LV hypertrophy) or microvascular disease. The technical details of these imaging modalities have been described in the European guidelines for cardiac nuclear imaging in 2008.[141] In accordance with the ESC guidelines for the management of stable CAD published in 2013, exercise ECG should be the initial step in the diagnostic evaluation of athletes with suspected CAD.[142] Individuals with inconclusive exercise ECG results could be referred for nuclear imaging. Similarly to CT, the indication to perform nuclear imaging should be weighted to the risk of radiation exposure.[135] The effective radiation dose for myocardial perfusion studies with novel scanners is <2 mSv for SPECT and <1 mSv for PET.[143] The accuracy of both PET and SPECT to detect CAD is very good, although PET may be preferred in balanced 3-vessel disease since PET permits absolute quantification of myocardial blood flow, representing the real added value of this technique, whereas SPECT can only provide semi-quantitative values (normalized to the maximum value), and can therefore not detect relative differences in perfusion.[144]

4. Criteria for differential diagnosis and risk stratification of specific cardiac diseases

4.1 *Hypertrophic cardiomyopathy*

Hypertrophic cardiomyopathy is one of the most common causes of SCD in young athletes and represents the basis for disqualification from competitive sports according to both American and European recommendations.[3,9] The diagnosis relies on the presence of a hypertrophied LV (i.e. LV wall thickness >15 mm) in the absence of cardiac or systemic disease capable of producing the same magnitude of LV hypertrophy.[145,146]

The diagnosis of HCM in young competitive athletes may be challenging when the extent of LV hypertrophy is mild and LV wall thickness is in the range of 13 mm to 16 mm, which identifies the 'gray-zone' of overlap between the physiologic adaptations to training and mild phenotypic expression of the disease.[1,5,121,147]

Cardiac imaging offers several clues for this differential diagnosis, having in mind that no single parameter may ultimately be diagnostic *per se* but final decision should always consider all clinical information available (*Table 7*).

The most useful morphologic criterion is the assessment of LV cavity size and geometry. Athletes in the gray zone typically show an enlarged LV cavity (end-diastolic diameter > 54 mm), while HCM athletes in the vast majority have a smaller cavity.[5] Indeed, the shape of LV chamber is altered in most HCM patients, due to the usual asymmetric, segmental, and centripetal development of the pathologic hypertrophy. However, in a few HCM athletes, especially those with apical phenotype, the cavity size may exceed this limit.[147] As a general rule, the development of physiologic LV hypertrophy in the context of the athlete's heart is consistently associated with LV cavity enlargement with an eccentric pattern, at difference from HCM.[20,103,104]

The highest degree of LV hypertrophy in athletes is seen in male gender, with values up to 15 mm in white and 16 mm in Afro-American athletes.[1,64] Less hypertrophy is found in female athletes, with values up to 11 mm in whites and 13 mm in Afro-Americans.[22,23]

Table 7 Cardiac imaging findings consistent with diagnosis of athlete's heart when left ventricular wall thickness is mildly increased, ranging from 13 mm to 16 mm

Diagnosis of athlete's heart in the gray-zone of left ventricular hypertrophy(13–16 mm)		
HCM	**Findings**	**Athlete's Heart**
+	Family history of sudden cardiac death/HCM	–
+	Major ECG abnormalities (ST segment/T wave inversion, wide, and deep Q waves)	–
+	Normal or reduced LV cavity size (<54 mm)	–
+	Abnormal LV cavity geometry and/or segmental LV hypertrophy	–
+	LV outflow tract obstruction	–
+	Abnormal LV diastolic relaxation/filling(septal e′ velocity < 8.0 cm/s and/or *E*/*A* ratio < 1.0)	–
+	Left atrial remodelling disproportionate to LV remodelling	–
+	Positive LGE on CMR	–
+	Unchanged LV wall thickness after detraining	–

CMR, cardiac magnetic resonance; HCM, hypertrophic cardiomyopathy; ECG, electrocardiogram; LGE, late gadolinium enhancement; LV, left ventricular.

To be noticed that LV hypertrophy is typically found in sport with a combination of high volume and pressure overload, such as rowing, canoeing, and x-country skiing.[1,20]

Athletes usually show a homogeneous distribution of wall thickness with absolute differences of <2 mm between the thickest and the thinnest segments of the LV. On the contrary, an asymmetric and heterogeneous pattern of LV hypertrophy represents a non-physiologic condition, or phenotypic expression of HCM.[5,104]

Athletes show a preserved LV chamber geometry with mitral valve normally located. Certain mitral abnormalities may be present in HCM athletes, such as elongation of mitral chordae, with systolic anterior motion and flow acceleration in the LV outflow tract, a phenomenon that has not been described in athletes.[148] Additionally, while LV outflow obstruction may not be evident under resting conditions, it could be precipitated by an exercise and demonstrated on stress echocardiography in HCM patients.[149]

Left ventricular systolic function is usually within the range of normality in both athletes and HCM patients. Only subtle differences in myocardial contraction can be detected by STE. Preliminary observations suggest that HCM with mild LV hypertrophy (12–16 mm) may have a reduction in longitudinal endocardial strain, with cut-off value <-15% able to identify pathologic hypertrophy with good accuracy (sensitivity 79%; specificity 67%). Therefore, values below this cutoff may be suggestive for pathologic LV hypertrophy.[84,150]

One of the most consistent features of the athlete's heart is the normal diastolic function, expression of preserved elastic, and recoil LV properties.[68,151] Conversely, in HCM patients LV diastolic function may present impairment as an expression of myocyte alteration and interstitial fibrosis. Few individuals may show an inversion of the *E*/*A* ratio, but most frequently in HCM a subclinical impairment is associated with a reduction of the e′ velocity on TDI.[5,147,151]

Cardiac magnetic resonance is indicated when echocardiographic images are not able to clearly identify all myocardial segments in order to exclude focal areas of hypertrophy (such as the apex and lateral wall). Indeed, CMR should be performed in all cases with associated marked ECG abnormalities and/or arrhythmias.[152] The higher contrast of CMR images between endocardial surface and the blood pool allows a better definition and distribution of LV hypertrophy and areas of focal hypertrophy. Most importantly, the use of LGE enables tissue characterization and identification of focal areas of myocardial fibrosis, commonly seen in patients with HCM.[153]

When the differential diagnosis remains still unresolved, useful information may come from detraining, with serial imaging testing (echocardiograms or CMR) after temporary interruption of training. It has been demonstrated that after a short period of detraining (3-month), regression of LV hypertrophy may be observed in athletes, while this is unlikely to occur in HCM.[66,154,155]

It is worthy to mention that left atrial size may not be particularly helpful in this specific scenario. Left atrial enlargement has been described in athletes as an expression of global cardiac adaptation to training and is typically associated with increased LV size, at difference than in HCM where LV cavity is usually of normal size or even reduced and LA appears disproportionately enlarged.[19,48] Additionally, while in older HCM patients LA enlargement is a common finding and is considered a reliable criterion for the diagnosis and risk stratification, in young and asymptomatic HCM patients with mild expression of the disease, this finding may not be present as well, with the apparent paradox that young athletes may have larger LA compared with young HCM patients.[5]

4.2 *Dilated cardiomyopathy*

The sports activities most often associated with LV chamber dilatation are those with high-isotonic/dynamic components, such as cycling, cross-country skiing, canoeing, and rowing.[1,4,20]

Left ventricular cavity enlargement in athletes should always be interpreted in the context of sport discipline participated and body size (it is advised to relate LV cavity diameter to BSAs, as previously reported) and is usually associated with increased wall thickness.[4,46,156] It has been reported that 38% of 950 elite athletes engaged in different sports disciplines showed increased LV end-diastolic diameter (>55 mm).[1] In a very large population of elite athletes, a substantial subset of 14% have a LV end-diastolic chamber markedly enlarged, with LV diameter > 60 mm, with 99th percentile corresponding to 65 mm.[4] In a group of very elite professional cyclists (n = 286) participating to the Tour de France, 45% had disproportionate chamber dilatation (LV diameter > 60 mm) and a small minority

also showed mildly impaired ejection fraction.[157] However it has been questioned whether these disproportionate cardiac adaptations were the results of illicit drug abuse.[51,157] Therefore, these findings could theoretically be a challenge for distinguishing the physiologic LV remodelling occurring in athletes from DCM.

It is worthy to notice that LV dilation in athletes is commonly associated with normal systolic function (EF > 50%). A large study involving more than 1000 Italian Olympic athletes of different sport disciplines showed normal LV ejection fraction in the entire study population, with lowest value being 53%, and fifth percentile equal to 55% (*Figure 8*).[68] Moreover, indices of diastolic filling and relaxation (by Doppler-echocardiography and TDI) are within normal limits.[68] In case of mildly reduced ejection fraction (i.e. EF ≥ 46%, <55%), it may be useful to assess LV function during exercise (by echocardiography or radionuclide imaging) (*Figure 9*). Absence of significant improvement of systolic function at peak exercise (i.e. an increase in ejection fraction <15% compared with the baseline value) is in favour of a pathological dilatation. Moreover, in doubtful cases, the assessment of peak oxygen uptake, which is consistently increased in relation to total heart volume can also help us to distinguish between physiologic and pathologic LV dilatation.[158]

Finally, STE might give additional information in terms of myocardial contraction. However, only few studies are available to date with somewhat diverse results on LV function at rest.[86,159,160] The results are, indeed, not strikingly different from normal ranges. So far, no study has directly compared myocardial strain in athletes and DCM.

Additional value is offered by the CMR with LGE. Cardiac magnetic resonance provides accurate measurements of actual dimensions and, in this context, the presence of positive LGE could be expression of myocardial fibrosis more consistent with a diagnosis of DCM.[161] Importantly, the absence of LGE does not exclude DCM.

4.3. *Arrhythmogenic cardiomyopathy*

Imaging criteria form an important part of the international diagnostic framework for arrhythmogenic cardiomyopathy (AC; previously defined arrhythmogenic right ventricular

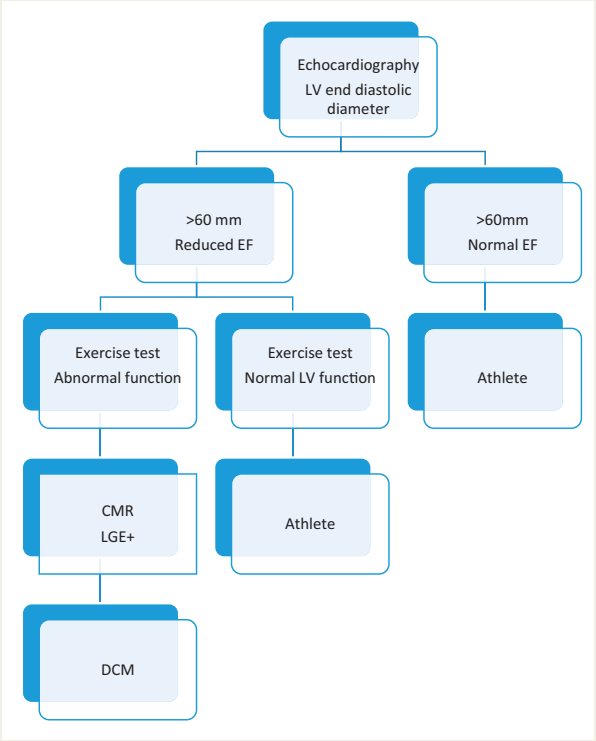

Figure 9 Proposed diagnostic algorithm for the differential diagnosis between physiological left ventricular cavity dilation in athletes and dilated cardiomyopathy. CMR, cardiac magnetic resonance; DCM, dilated cardiomyopathy; EF, ejection fraction; LGE, late gadolinium enhancement; LV, left ventricle.

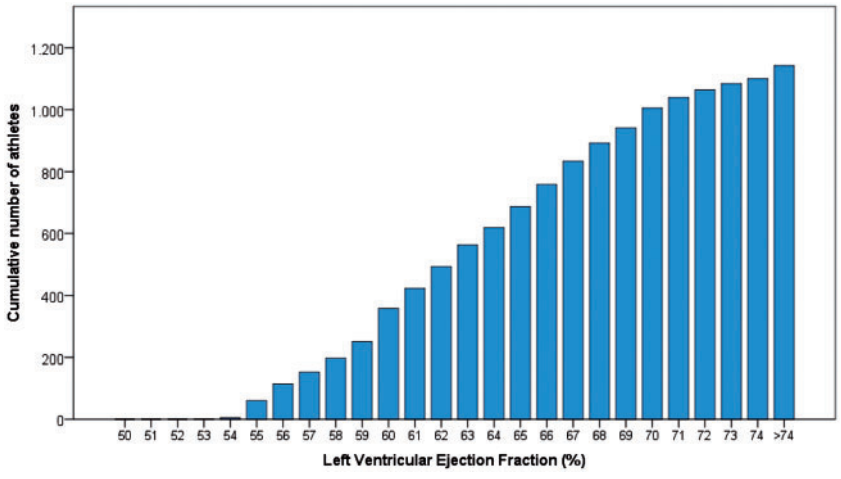

Figure 8 Left ventricular ejection fraction measured by echocardiography in a population of 1145 Olympic athletes (age 26 ± 5 years; 61% male), free of cardiovascular disease, engaged in different sport disciplines. LV ejection fraction was normal in the entire study population with the lowest value 53% and fifth percentile 55%. *Data from Caselli S et al. Patterns of Left Ventricular Diastolic Funcrion in Olympic Athletes. J Am Soc Echocardiogr 2015;28:236–244.*

cardiomyopathy/dysplasia, ARVC/D), as outlined in the modified Task Force criteria proposed in 2010, and in the recent EACVI recommendations.[14,111] Electrical changes, which often form the hallmark of the diagnosis of AC should be interpreted in the context of the imaging findings: these include repolarization changes in the right precordial leads (although not very specific)[7,162]; low right precordial QRS amplitudes; epsilon waves; late potentials (especially when 3 out of 3 criteria); frequent ventricular premature beats or non-sustained ventricular tachycardia from the RV (especially when not from the RVOT)[7,163]; or inducibility during EP study.[164] Of relevance, it should be noted that electrical changes in athletes could precede over long-time the morphological changes in athletes with AC.[61] Although 2D echocardiography provides a readily available imaging tool, it has important limitations for visualizing the complex geometry of the RV. Therefore, modern imaging relies more on CMR.

Athlete's hearts are by definition larger than untrained hearts. Moreover, it is known that endurance exercise selectively promotes RV dilatation due to the increase in RV wall stress during high cardiac output conditions.[76,164,165] Many endurance athletes have slightly larger RV than LV volumes.[165,166] Physiological RV remodelling is characterized by consistent increase in RV inflow and outflow segments, at difference from the predominant increase of the outflow tract observed in AC patients.[167] The AC Task Force criteria proposed defined dimensional criteria in the presence of regional wall motion abnormalities.[111] With regard to RV size, the criteria are based on data derived from AC patients vs. normal controls, not including healthy athletes, which represents a potential limitation. Actually, up to 30% and 60% of athletes have RV dimensions that would match respectively the 'major' and 'minor' Task Force criteria.[76,95] Right ventricular dilatation in athletes may be suggestive for AC only when is really extreme.[7,96,168] Therefore, we have proposed that only major dimensional criteria, indexed by BSA should be used to define RV enlargement in athletes: specifically, RVOT > 19 mm/m^2 in long axis, and/or >21 mm/m^2 in short axis, and/or RV end-diastolic volume on CMR ≥110 mL/m^2 in males and ≥100 mL/m^2 in females.[7,76,163] Nevertheless, RV dimensions by themselves are insufficient criteria to distinguish physiologic from pathologic RV dilatation, and need to be associated with regional wall motion abnormalities.[111] Other useful measures that have shown specificity for AC include the ratio (on echocardiography) of RV inflow dimension (in the apical view)/LV end-diastolic dimension (parasternal long-axis view) >0.9, or a ratio of RVEDV/LVEDV >1.2 on CMR.[7]

Functional measures are more important than pure dimensions. Again, CMR may perform better than echocardiography. Regional akinesia, dyskinesia, or aneurysmal deformation are important findings, since they are present in more than half of AC patients. Also measures of global dysfunction are useful: e.g. RV fractional area change on echocardiography <33%, or RVEF ≤40 on CMR.[7,163] With regard to STE, RV global longitudinal strain (RV-GLS) and strain rate in athletes are comparable to non-athletes.[95,96] On the contrary, AC patients may show a subclinical RV dysfunction with reduced RV-GLS, and further decrease is observed in those AC patients regularly engaged in sport activities.[169] Additionally, mechanical dispersion of right ventricular contraction detected by STE may represent an early predictor of future arrhythmic events.[98,170] While LGE on CMR is seen in >40% of familial forms of AC (due to desmosomal mutations), it is still not part of the current AC Task Force criteria. Often LGE is present also or exclusively in the LV, as it is recognized that LV involvement of familial AC is common.

New data indicate that morphologic and functional evaluation of the RV both with echocardiography and CMR during exercise (i.e. not at rest) can be of help in the differential diagnosis of pathologic RV remodelling.[81,94,171] Indeed, athletes with subclinical AC may have volumetric or functional values within normal range at rest, while showing subnormal augmentation of RV systolic function during exercise.[80,94,163,172] *Table 8* summarizes the most common criteria that may help in differential diagnosis between physiologic RV adaptation in athletes as opposed to AC.

4.4 Left ventricular non-compaction

Left ventricular non-compaction is a relatively novel cardiomyopathy that is characterized by prominent myocardial trabeculations and deep inter-trabecular recesses.[173–176] Knowledge relating to the precise stage of development and the natural history of the disorder is still incomplete, however available data are suggestive of a morphologically and clinically heterogeneous disorder. Whereas some individuals present with overt heart failure and potentially fatal arrhythmias, others may remain asymptomatic.[175] The clinical diagnosis is currently reliant on three proposed echocardiographic criteria and are based on the demonstration of high non-compacted to compacted ratio within the LV myocardium.[173,174,177]

Advances in tissue harmonics and image resolution in echocardiography have coincided with increased reports of features consistent with LVNC in patients with heart failure,[176] as well as in low-risk cohorts including sickle cell patients[178] and athletes,[179–184] particularly those of African/Afro-Caribbean origin. A study of over a 1000 asymptomatic athletes demonstrated that 18% exhibited increased LV trabeculations and 8% fulfilled echocardiographic criteria for LVNC, more commonly in black athletes.[179] A small proportion (0.9%) of these athletes also exhibited concomitant T-wave inversion and reduced indices of systolic function that may be considered diagnostic of LVNC, a finding that was also reported in Dutch football players.[180]

At the moment is debated if these findings could be considered incomplete expression of LVNC phenotype that may be unmasked through intensive exercise training, or conversely, if they may represent just atypical features of cardiac adaptation. The precise mechanism for the development of increased LV trabeculations in low-risk cohorts is unclear, however, it has been observed that an increased cardiac preload is the common factor in situations associated with increased LV trabeculations, such as heart failure, chronic anaemia, and athletic training. It is therefore possible that an increase in preload may unmask a pre-existing trabeculation. The hypothesis is supported by a longitudinal study, using the pregnancy model to assess the impact of a physiological increase in cardiac loading conditions on LV trabeculations.[185]

A multimodal diagnostic approach is recommended for the diagnosis of LVNC in athletes.[184] We propose the following guidance on the assessment of athletes presenting with increased LV trabeculations, here defined as showing a non-compacted to compacted (NC/C) layer ratio >2.0 in systole on echocardiography or >2.3 in diastole on CMR (*Table 9*).[173,186] Cardiac symptoms or a family history of heart failure, or premature SCD in an athlete fulfilling criteria for

Table 8 Clinical and multi-modality imaging findings that may help in differential diagnosis between physiologic RV adaptation as opposed to AC

Differential diagnosis between athlete's heart and AC		
AC	**Findings**	**Athlete**
+	Family history of sudden cardiac death/AC	-
+	Anterior T wave inversion on ECG	-
+	Ventricular arrhythmias with LBBB morphology	-
+	Exercise induced VT	-
+	RV size exceeding major Task Force Criteria for echocardiography or CMR (consider only indexed values)	-
+	Regional wall motion abnormalities (akinesia or dyskinesia) on cardiac imaging.	-
+	Global RV dysfunction on echocardiography (RVFAC < 33%) or CMR (RVEF ≤ 40)	-
+	Abnormal RV function on exercise echocardiography/CMR	-

AC, arrhythmogenic cardiomyopathy; CMR, cardiac magnetic resonance; ECG, electrocardiogram; LGE, late gadolinium enhancement; LBBB, left bundle branch block; RV, right ventricle; RVEF, right ventricular ejection fraction; RVFAC, right ventricular fractional area change; VT, ventricular tachycardia.

LVNC favours cardiac pathology. Information from screening of first-degree relatives for features of LVNC is invaluable but not always practical. Additional echocardiography features of LVNC include low ejection fraction that does not improve (by at least 20%) with moderate exercise (70% of the maximum predicted heart rate), a mean e' < 9 cm/s at echocardiography, and a thickness of compacted layer in systole <8 mm.[187] During maximal exercise testing, features favouring LVNC include peak oxygen consumption less than predicted value from healthy controls, or occurrence of complex ventricular arrhythmias. Abnormal myocardial strain patterns are in the experimental phase for this condition but an abnormal parameter may suggest a disease process.[188] Finally, detection of areas of LGE within the LV on CMR is in favour of a cardiomyopathic process.[189]

Table 9 Findings consistent with diagnosis of athlete's heart or left ventricular non-compaction when increased trabeculations are occasionally found on echocardiography in athletes

Athletes with increased trabeculations		
LVNC	**Findings**	**Athlete**
+	Family history of sudden cardiac death/LVNC	-
+	Symptoms	-
+	Reduced LV systolic function (EF < 50%)	-
+	Reduced thickness of compact layer	-
+	Late gadolinium enhancement on CMR	-
+	T-wave inversion on ECG	-
+	Left bundle branch block on ECG	-
+	Exercise induced VT/AF	-
+	Abnormal diastolic function	-

AF, atrial fibrillation; CMR, cardiac magnetic resonance; ECG, electrocardiogram; LV, left ventricle; LVNC, left ventricular non-compaction; VT, ventricular tachycardia.

4.5 Aortic root disease and bicuspid aortic valve

Remodelling of the aortic root may be expected to occur in athletes as a consequence of haemodynamic overload with exercise training.[50,74,190–192] Technically, aortic root diameter measurements should be made from the parasternal long-axis view using the leading edge-to-leading edge convention and preferring 2D measurements rather than M-mode measurements.[73]

Measurements ideally should include: (i) the aortic valve annulus (hinge point of aortic leaflets), (ii) the sinuses of Valsalva, (iii) the sino-tubular junction, and (iv) the proximal ascending aorta (*Figure 10*).[73]

Several observational studies performed in the general non-athletic population reported that height and body size are the most relevant determinants of aortic root size.[75,193–195] Iskandar and Thompson[75] in a meta-analysis including a cohort of 5580 elite athletes and 727 controls reported that athletes have greater aortic root diameters compared with control subjects; however the effect of exercise training on aortic size was small and most pronounced in those engaged in endurance disciplines. Other studies on different athletic populations reported a low prevalence of aortic enlargement (>40 mm in males) in athletes.[50,74,190,191,196] Pelliccia *et al.*[50] in a large cohort of 2317 elite athletes reported 1.3% of aortic root enlargement (17 males) with the 99° percentile equal to 40 mm in males and 34 mm in females. This value is recommended as cut-off for evaluating aortic root diameters in elite athletes. In order to avoid the confounding effects of body size and age, the American College of Cardiology and the American Heart Association have recently proposed the use of *Z*-scores to identify subjects with significant aortic root dilation (i.e. *Z*-score > 2).[11]

In athletes with an aortic root dimension above the reference values, the presence of associated pathologic conditions including Marfan Syndrome or BAV should be excluded.[197,198] In athletes with dilated aortic root, even in the absence of recognized structural systemic/cardiac disease, a periodical clinical and diagnostic assessment with non-invasive imaging should be recommended, to monitor aortic root dimensions over time and recognize an accelerated enlargement.

Bicuspid aortic valve is one of the most common congenital cardiac anomalies, with prevalence between 0.5% and 2% in the general population.[199] In large athletes population the prevalence of BAV has been reported as 1%.[200] Inherited disease is described in up to

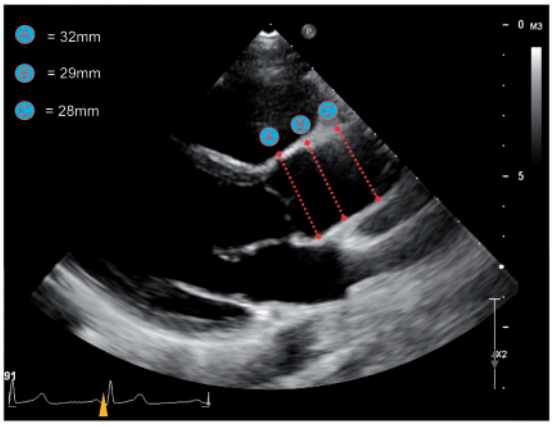

Figure 10 Parasternal long-axis view of the aortic root and ascending aorta in end-diastole in a 18 year-old male soccer player. The measurements of aortic root at sinuses of Valsalva (A), sinotubular junction (B), and proximal ascending aorta (C) are reported.

10–17% of first-degree relatives.[201] As such, early detection of this entity is of great importance, particularly due to the fact that in up to 30% various complications can interfere.[202] Beside possible progression to valve dysfunction (stenosis or regurgitation), individuals with BAV present with larger dimensions of the aortic sinus, ascending aorta, and aortic arch compared with those with a tricuspid aortic valve. They harbour an increased risk for progression and, in the very worst case, aortic dissection.[203,204] However, not all individuals with BAV seem to be at risk for progressive aortic dilation, and thus it is important to identify athletes at highest risk for aortic complications.[200] This can only be achieved by regular echocardiographic follow-up. Furthermore, BAV may be associated with additional diseases (particularly in case of an autosomal-dominant inheritance pattern). As such, coarctation of the aorta, interrupted aortic arch, patent ductus arteriosus, coronary anomaly or hypoplastic left heart, as well as Williams or Turner syndrome have to be excluded.[205–207]

Only a few studies have addressed the outcome of BAV in the general population: in one study, 25% to 42% of subjects with BAV required surgery for symptomatic valve disease, LV dysfunction, ascending aortic dilation, or endocarditis.[204,208] However, overall life expectancy is not decreased in patients with BAV.[204,209] A recent international registry on BAV reported that the presence of raphe was associated with higher prevalence of valvular dysfunction and increased rates of surgery.[210] Endocarditis may complicate BAV disease in about 10–30% during life, however, antibiotic prophylaxis is currently not routinely recommended in isolated BAV.[211]

Outcome data on athletes are sparse but generally, adverse outcome depends on various predictors (e.g. age > 30–50 years and aortic dimension of >40 mm or, at least, moderate aortic valve dysfunction at baseline).[200,204,212,213]

Bicuspid aortic valve may be difficult to diagnose in athletes and may sometimes be missed; careful physical examination may reveal a mild murmur and/or a characteristic mid-systolic 'click'. Echocardiography is the imaging modality of choice when BAV is suspected. The number of leaflets, leaflet fusion, and the presence of a 'raphe' can be reliably determined in the short-axis view, while systolic doming and eccentric diastolic closure of the leaflets can be visualized in the long-axis view. Two- or three-dimensional transoesophageal echocardiography may further improve the accuracy for diagnosis and correct assessment of BAV (*Figure 11*).[214] Associated coarctation of the aorta can be suspected on echocardiography but needs to be confirmed by CT or CMR. Furthermore, Doppler echocardiography allows accurate assessment of valve dysfunction. Presence of valvular regurgitation or stenosis should be properly assessed according to most recent guidelines.[215,216] In case of valvular regurgitation and LV cavity dilation, the latter should be interpreted in the context of sport discipline participated and body size, using normalized values as advised.[4,12] Finally, it may be appropriate to obtain an exact assessment of the ascending aortic diameters by an additional CT or CMR scan at least as an index at 'baseline' and in case of aneurysmatic aortic dilation with potential indication for surgery.[217]

4.6 Mitral valve prolapse

Mitral valve prolapse (MVP) is the most common valvular disease in the general population, with an estimated prevalence of 2–3%; it is defined as an abnormal systolic displacement of one or both leaflets into the left atrium below the mitral annulus, due to structural elongation or abnormal distensibility of the mitral valve.[218] The main echocardiographic characteristic is the displacement of one or both leaflets >2 mm beyond the annulus (from the parasternal long-axis view) associated with maximal leaflet thickness ≥5 mm (in the classic MVP) or <5 mm (in the non-classic MVP).[219–221] Although MVP is generally regarded as a benign condition, the outcome is widely heterogeneous, and complications such as mitral regurgitation, atrial fibrillation, congestive heart failure, endocarditis, ventricular arrhythmias, and SCD have been reported.[220,222,223] In detail, the estimated rate of SCD in MVP ranges from 0.2%/year to 0.4%/year in prospective follow-up studies and recent evidence seems to suggest that MVP is an underestimated cause of arrhythmic SCD, mostly in young adult women.[15,220,224] Most importantly MVP has been reported to account for a large proportion (as high as 11%) of the overall causes of SCD in young competitive athletes.[225]

Echocardiography is the imaging technique of choice for the diagnosis and characterization of MVP and is generally indicated when the typical end-systolic murmur associated with mid-systolic click is identified on physical examination. The entity of leaflet prolapse, characteristics and quantification of mitral regurgitation jet, LV size and function, and left atrial size should be reported and periodically re-evaluated. Mitral valve regurgitation should be assessed according to most recent guidelines.[215] In presence of LV cavity dilation, the specific impact of mitral regurgitation should be interpreted in context of athlete's type of sport participated and body size (specifically in endurance athletes LV is considered dilated when end diastolic diameter exceeds 35 mm/m^2 in males and 40 mm/m^2 in females).[4,12] In case of ventricular arrhythmias on resting or exercise ECG (especially those with right bundle branch block morphology) a CMR should be requested in order to exclude the presence of areas of fibrosis which may be correlated with severe ventricular tachy-arrhythmias.[15]

4.7. Myocarditis

Myocarditis is an inflammatory disease of the heart muscle that occasionally affects young individuals including athletes. The viral aetiology

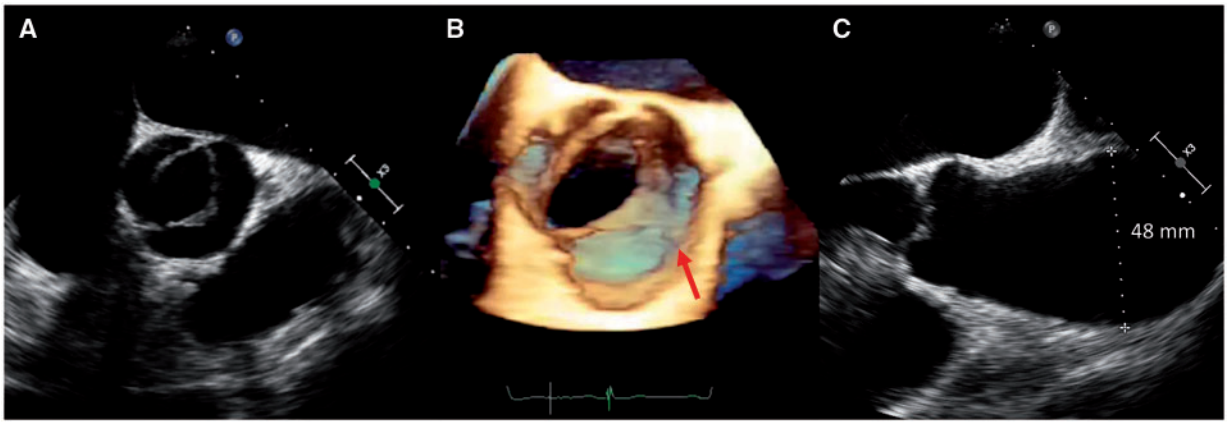

Figure 11 Transesophageal echocardiogram of a 24-year old patient with bicuspid valve. Two-dimensional imaging showing bicuspid valve in systole characterized by the antero-posterior pattern (A); Real-time three-dimensional imaging showing the raphe between right and left coronary cusps (red arrow, panel B); long-axis view of the aorta showing a marked dilation of the ascending aorta with a maximal diameter of 48 mm (C).

is largely predominant in developed countries.[226,227] The clinical course is variable ranging from mildly symptomatic to fulminant disease. Some patients heal completely with the elimination of pathogens and resolution of the inflammatory process, but in others, the activation of autoimmunity may evolve in a chronic disease and/or DCM.[228,229] During all the phases of the disease, the interstitial oedema, myocardial necrosis, and fibrosis represent the myocardial substrate for the electrical instability.[225,227,228] In this scenario, the sport activity may trigger malignant arrhythmias which may ultimately culminate in SCD.[3,225]

The clinical suspicion of myocarditis may rise from clinical history of a recent respiratory or gastrointestinal tract infection. Patients may report fever, chest pain, palpitation, and decreased physical performance; laboratory testing may reveal increased inflammatory markers (C-reactive protein and erythrocyte sedimentation rate) associated with an otherwise unexplained rise in cardiac troponin.[227] However, it should be noticed that clinical presentation might be subtle and inflammatory markers only mildly elevated.

Electrocardiographic findings are not specific and include most commonly repolarization abnormalities and atrial or ventricular arrhythmias.[3,226] Indeed, isolated or complex ventricular arrhythmias during an exercise test may be one of the first manifestations of the disease.

On echocardiography, the LV may be dilated with thin myocardial walls resembling DCM, or non-dilated with increased myocardial wall thickness due to myocardial oedema. Global systolic function may be mildly reduced and, of relevance, focal regional wall motion abnormalities may be observed. Concomitant pericardial effusion may suggest pericardial involvement.[227]

Over the last decade CMR has acquired an increasingly role for the diagnosis of myocarditis: an international consensus group reported that, in the appropriate clinical context, the diagnosis of myocarditis is defined by at least 2 of 3 of the following findings: (i) regional or global myocardial signal intensity increase in T_2-weighted images; (ii) increased global myocardial early gadolinium enhancement ratio between myocardium and skeletal muscle in gadolinium enhanced T_1-weighted images; (iii) at least one focal lesion with non-ischaemic regional distribution in inversion recovery-prepared gadolinium enhanced T_1-weighted images.[230]

Furthermore, the identification of LGE may confer prognostic information, since it is a strong independent predictor of events during follow-up.[231–233]

The clinical significance of persistent area of LGE in an asymptomatic athlete with clinically healed myocarditis is still unresolved; it is reasonable to assume that after clinical resolution of the diasese the absence of symptoms, LV dysfunction, ECG abnormalities, and arrhythmias on 24-h Holter ECG/exercise test represent a low-risk condition and the athlete may resume training and competition under strict clinical surveillance.

4.8 *Congenital coronary artery anomalies*

The estimated prevalence of congenital coronary artery anomalies (CCAA) in the general population is quite variable, depending on both the definition and the source of data, ranging from 0.21% to 5.79%. Despite the low prevalence, CCAA are well recognized as major cause of SCD in competitive athletes, accounting for about 17% of such deaths in the USA and for 16% in Italy.

However, not all CCAA have the same prognostic impact, the anomalies considered at risk of SCD on effort include an anomalous origin from a wrong aortic sinus, anomalous origin from the pulmonary artery and myocardial bridge (MB).

The diagnostic algorithm for athletes with suspect CCAA is shown in *Figure 12*.

Anomalous coronary artery origin from a wrong aortic sinus (either the right coronary artery from the left or the left coronary artery from the right sinus) can present a variable course of the proximal tract, i.e. pre-pulmonic, retro-aortic, intra-septal sub-pulmonic, or inter-arterial and the latter is considered at risk of SCD.[234,235]

To the diagnosis, unfortunately, the ECG and even maximal exercise test are often normal. If the index of suspicion is sufficiently high, because of potential clinical markers (such as exertional syncope, chest pain, or arrhythmias), the diagnosis can be defined non-invasively by transthoracic (or transoesophageal) echocardiography as a first step.[235] It has been shown that visualization of the ostium and

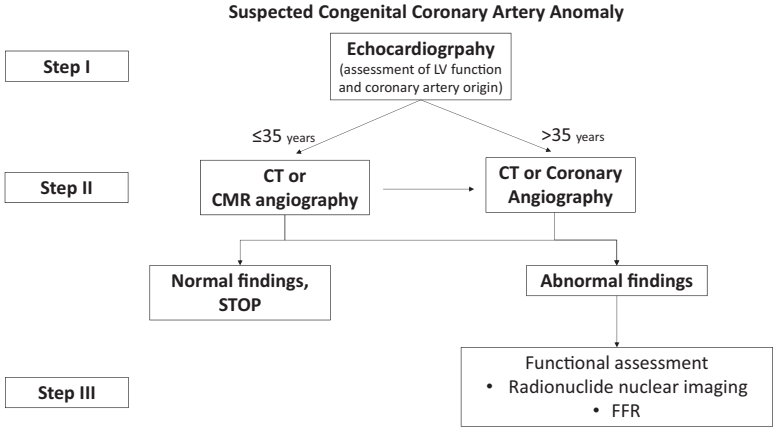

Figure 12 Diagnostic algorithm for athletes with suspected coronary artery anomalies. The first step is represented by the evaluation of LV global and regional function by echocardiography and identification of the coronary ostia from the parasternal short-axis view. The second step is the anatomic evaluation of coronary arteries by Computed Tomography (CT), Magnetic Resonance Angiography (MRA) or coronary angiography. When abnormalities are found, the third step is represented by functional studies, which may guide in understanding the clinical impact and help in the patient management. CT, computed tomography; FFR, fractional flow reserve; LV, left ventricle; CMR, cardiac magnetic resonance.

proximal course of the left main and right coronary arteries is possible in over 98% and 80% of athletes.[217]

The failure to demonstrate that a CA originates from its proper Valsalva sinus requires further anatomic confirmation with CT, CMR angiography or coronary angiography based on age and risk profile (*Table 6*; *Figure 12*).[235,236] In patients with a clinical suspicion of CCAA, the European Society of Cardiology recommends CT and the American Heart Association either CT or CMR angiography, the latter preferred due to radiation concerns.[237,238]

After the diagnosis, functional assessment of CCAA for clinical management and advise relative to sport participation is challenging in asymptomatic people. Aim of the functional assessment is detection of exercise-induced ischaemia. To the scope, nuclear scintigraphy and/or stress echocardiography and coronary angiography should be performed. Intravascular ultrasound (IVUS) of the proximal vessel has been proposed to evaluate lesion severity based upon the amount of hypoplasia and the degree of lateral compression; finally, fractional flow reserve (FFR) assessment is also recommended.[235] Intravascular ultrasound and FFR should be performed both at baseline and with pharmacological stress.

Myocardial bridge consists of a major epicardial CA, usually the left anterior descending CA, coursing deep within the myocardium.[239,240] Effort-induced ischaemia has been attributed to tachycardia, which increases the myocardial oxygen requirement and reduces the coronary flow occurring in diastole. Diagnosis of MB can be achieved non-invasively by CT which can define the anatomic characteristics, such as the length and depth of the intramyocardial course of the CA, even if haemodynamic characteristics cannot be derived. Coronary angiography confirms the diagnosis by showing the classic 'milking effect' (i.e. a transient compression in systole, that can be accentuated by intracoronary nitroglycerin injection). Intravascular ultrasound can reveal the characteristic 'half-moon' sign and the extent of phasic arterial compression, besides proximal plaque and negative arterial remodelling.[239]

The major challenge, however, remains the criteria to guide management: crucial to risk stratification is the demonstration of exercise-induced ischaemia.[239,240] Reversible perfusion defects can be detected by stress nuclear imaging (see Section 3.6). Alternatively, reversible ischaemia due to MB can be detected by combined stress CMR perfusion and wall motion imaging. Coronary physiological measurements across a MB during pharmacological infusion are also valuable; i.e. intracoronary Doppler can reveal the distinctive 'fingertip' phenomenon and iintracoronary pressure measurement with values of fractional flow reserve (FFR) <0.75 suggests ischaemia.

5. Conclusion

This document offers a comprehensive overview of the cardiac physiologic remodelling as well as the changes associated with pathologic conditions, detectable in athletes by the most advanced imaging techniques. The correct approach to the diagnosis and management of cardiac pathologic conditions in athlete's populations represents nowadays a largely recognized clinical need for clinical cardiologists and sport medicine specialists.

This document provides the clues for a timely and correct identification of the most relevant cardiac diseases, according to the most common clinical scenarios. Adherence to this document will help clinicians to require imaging testing according to the recognized indications and provides the keys for appropriate interpretation of result, in the context of the athlete's gender, age, race, and sport participated.

Eventually, we are confident that appropriate use of cardiovascular imaging techniques in the athlete's population will facilitate a more cost-effective cardiovascular evaluation, contributing to safer competitive sport participation.

Conflict of interest: Doctors Pelliccia, Caselli, Sharma, Basso, Bax, Corrado, D'Andrea, D'Ascenzi, Di Paolo, Edvardsen, Gati, Galderisi,

Nchimi, Nieman, Papadakis, Pisicchio, Schmied, Popescu, Habib, Grobbee, and Lancellotti have nothing to disclose.

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